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German COIL Efforts: Status and Perspectives

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ABSTRACT

Historically, COIL research in Germany has started with microwave excitation of an oxygen flow. But soon all efforts have been devoted to the chemical generation of excited singlet oxygen and have eventually given rise to a supersonic 10 kW class rotating disk driven device. A diode based diagnostic provides data of small signal gain and cavity temperature which emphasize the role of iodine injection for different penetration conditions. Heat release can lead to substantially higher temperatures as expected from adiabatic expansion. Power extraction is found to be in good agreement with theoretical predictions. Alternatively, small scale liquid jet generator experiments show encouraging 60 % efficiency. Besides air defense related applications and a study on space debris removal, results are given which are pertinent to the decommissioning of nuclear installations. In particular, laser cutting of concrete at 1.3 μm is demonstrated and theoretically scaled up to relevant power levels.

Keywords: chemical lasers, oxygen, iodine, power extraction, decommissioning

1. INTRODUCTION

Historically, it all started in 1987 with a helium and oxygen gas mixture flowing thru a 2.45 GHz microwave discharge. At that time the laboratory was heavily involved in different types of electrically excited lasers with special emphasis on CO_2 and CO lasers. Therefore, it seemed quite natural to investigate the possibility to electrically excite the oxygen molecule; an idea that has become very popular, recently. The historic device is shown in Fig. 1. At that time the efficiency of electrically generating $O_2(^1\Delta)$ was so low that no further attempt was undertaken to start real laser experiments. Encouraged by the results obtained with the chemical excitation of $O_2(^1\Delta)$ in the U.S. the decision was taken in Germany to redirect the research to the chemical excitation as well and to abandon the electric discharge scheme. From there on all major efforts have been aimed at the investigation of a 10 kW rotation disk driven device. Major achievements on that road will be reviewed in chapter 2.1. More recently growing interest has been given to the liquid jet oxygen generator and its scaling potential as compared to the rotating disk concept. The second part of this paper addresses present and future applications. Since most applications require high beam quality this particular issue will be discussed in chapter 3.1. Subsequently, three different application areas will be described: the tactical air defense, the laser supported space debris removal, and the laser decommissioning of nuclear installations. This also includes a comparison of investment and running costs of COIL as compared to its major laser competitors.

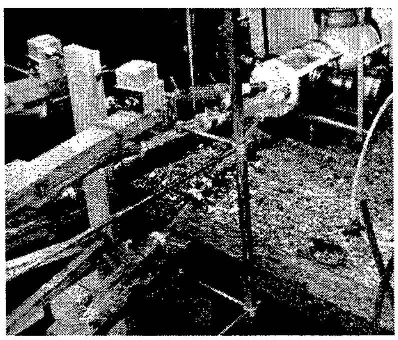

Fig. 1: Historic microwave discharge in oxygen.

2. COIL LASER RESEARCH AND DEVELOPMENT

2.1 Review of German 10 kW class COIL investigations

Most of the work has been concentrated on a rotating disk driven device using a nozzle bank with 20 elements and subsonic iodine injection[1]. For base line conditions the laser is operated with a chlorine mass flow of typically 0.5 mol/s and a He:Cl_2 ratio of 3. The Mach number after the supersonic expansion is close to 2. As shown in Fig. 2 the O_2H^- molarity and rotation speed of the disk pack have been varied over a wide range and the utilization approaches typically

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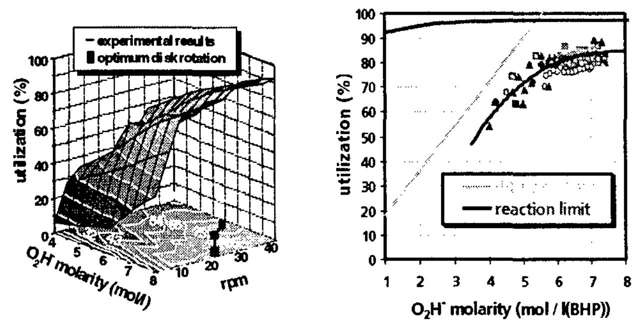

Fig. 2: Utilization as a function of O_2H^- and rpm (left) and compared to diffusion and reaction limits (right).

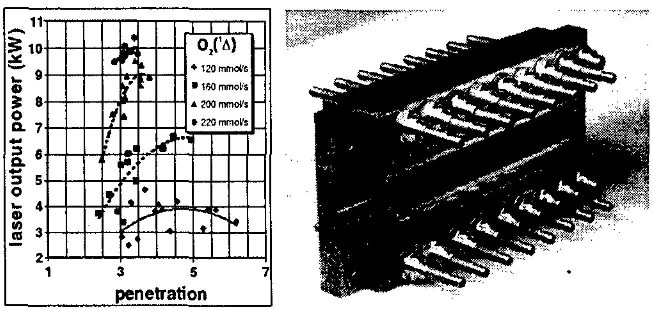

Fig. 3: Laser power as a function of penetration (left); nozzle bank (right).

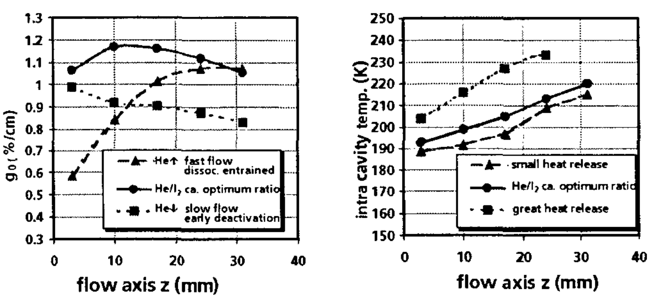

Fig. 4: a) Small signal gain, and b) cavity temperature in flow direction with I_2 = const.

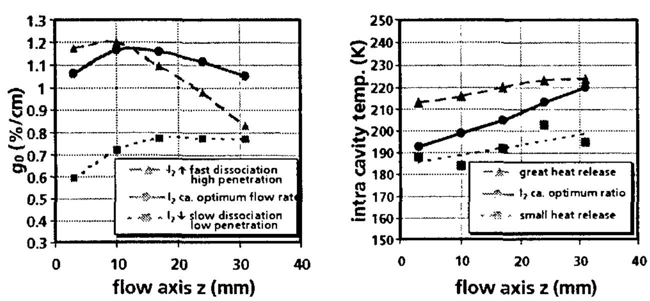

Fig. 5: a) Small signal gain, and b) cavity temperature in flow direction with He/I_2 = const.

90% for optimum operating conditions. On the right part of Fig. 2 a collection of data points demonstrates the transition from a diffusion limited to a reaction limited model as a function of the O_2H^- molarity in the BHP. For power optimization one of the most important issues is the influence of iodine penetration: the latter basically reflects the ratio of the momentum of the iodine flow to the main flow. As can be seen in Fig. 3 the maximum laser output power is obtained within a narrow range of penetration values at high singlet oxygen flow rates. This behavior is much more relaxed at lower singlet oxygen flow rates. The nozzle bank used in all those experiments is shown on the right hand side of Fig. 3.

A considerable step in COIL research and understanding occurred with the advent of more sophisticated diagnostic tools, in particular the diode based optical diagnostics as provided by the PSI Corporation[2]. An appropriate example is given by the measurements[3] of small signal gain and temperature along the flow axis. The major goal was to investigate the impact of the secondary flow by excursion of parameters with respect to optimum lasing conditions which will be represented by a full line in the following figures.
In the first case, we keep the iodine concentration constant and vary the helium flow rate. Increasing the latter accelerates the flow and leads to a very substantial entrainment of the dissociation, and accordingly, to the small signal gain along the flow axis as shown in Fig. 4a. On the other hand, decreasing the helium flow rate decelerates the flow and the small signal gain readily starts with a high value at the nozzle exit plane but early deactivation occurs and thus the small single gain decreases monotonically. Fig. 4b shows how this behavior translates to the cavity temperature: whereas the fast flow exhibits a small heat release the slow flow is governed by a quite substantial heat release and thus the cavity temperature increases dramatically along the flow axis and exceeds 230 K 25 cm after the nozzle exit plane.

In the second case we keep the He/I_2 ratio constant while changing the iodine flow rate. Increasing the iodine flow rate leads to a fast dissociation and thus the small signal gain exhibits highest values at the nozzle exit plane but sharply decreases thereafter due to deactivation. This situation reflects a high iodine penetration. Decreasing the iodine flow rate limits the small signal gain to rather low values and characterizes a low penetration situation (Fig. 5a).

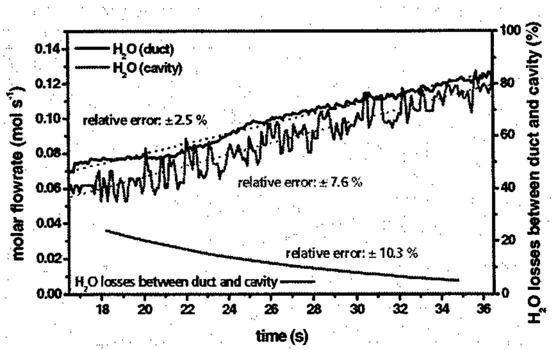

Fig. 6: Water vapor in transport duct and cavity (upper traces); H_2O losses (bottom trace).

Accordingly, great heat release occurs for high penetration and small heat release with temperatures ranging between 190 K and 200 K is found for low penetration, as shown in Fig. 5b.

Another example relates to the water vapor measurement. Using the PSI diagnostic water vapor concentration is measured in the transport duct prior to the nozzle bank and in the cavity: the upper curve in Fig. 6 corresponds to the duct measurement and the lower curve which is characterized by substantial fluctuations corresponds to the cavity measurement. The fluctuations arise because of the lower signal to noise ratio obtained in the cavity measurement. At the bottom of Fig. 6 the total water vapor losses between duct and cavity positions is shown as a function of time: they range from about 20 % to 5 % within the measured time interval. This measurement strongly suggests that water condensation is not negligible during the expansion of the laser active gas.

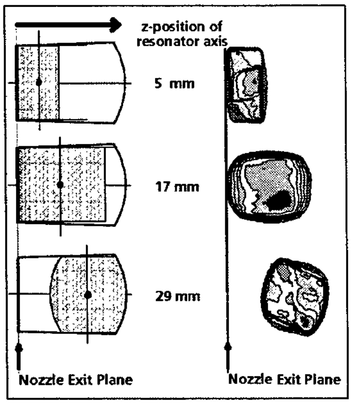

Fig. 7: Beam pattern for different outcoupling configurations.

Power extraction has been studied[4] using a variable slit aperture in front of the outcoupling mirror. Fig. 7 shows a two-dimensional burn pattern for three different resonator outcoupling configurations: for a small aperture resonator optically centered at 5 mm from the nozzle exit plane, for a fully opened resonator centered at 17 mm, and for a resonator centered at 29 mm but limited by the downstream cavity structure. A more detailed measurement of the power extraction is obtained by either varying the width of the slit aperture or by translating a constant aperture slit along the flow axis. The corresponding geometry is schematically shown in Fig. 8. Increasing the width of the slit in front of the outcoupling mirror leads, as expected (and shown in Fig. 9), to a higher fraction of the normalized laser output power: for a slit width of 30 mm the maximum available output power has already been reached. For smaller widths the power fraction decreases down to 40 %. At that point the laser operation is discontinued and the flow in the cavity chokes: all the remaining power is converted into translational energy as shown by the open dots. This experimental situation is supported by a saturated gain model first derived by Hager[5] of the AFRL: whereas the dotted line reflects the model with constant pressure the full line corresponds to the same model but with variable pressure. Its validity is, of course, limited

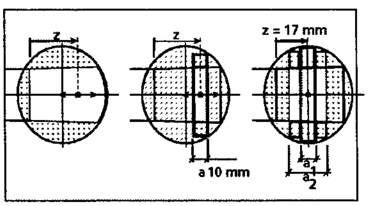

Fig. 8: Schematic of outcoupling geometries.

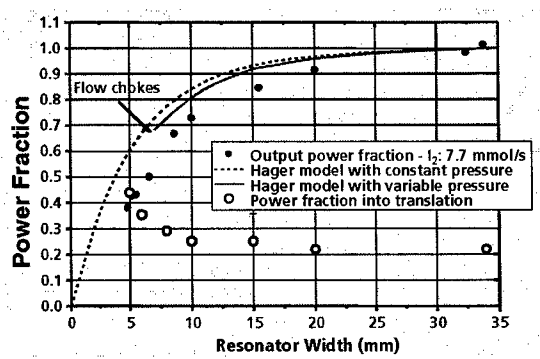

Fig. 9: Laser power fraction as a function of resonator width.

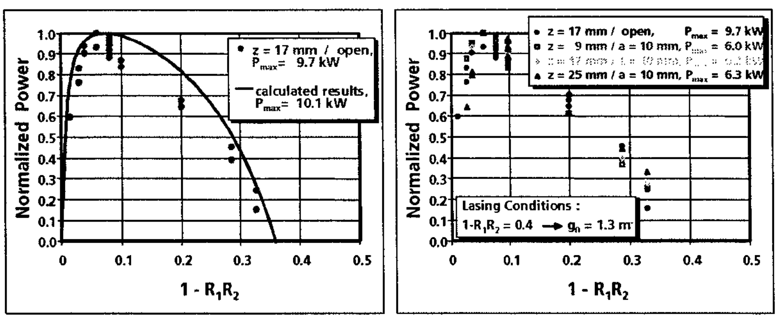

Fig. 10: Rigrod plot for a) an open resonator, and b) an obscured resonator aperture.

to the point where the laser active flow chokes. In general, Fig. 9 demonstrates a rather good agreement between theory and experimental data.
Rigrod analysis is another way to investigate power extraction properties. Fig. 10a exhibits an experimental and theoretical Rigrod plot obtained with an open resonator optically centered at 17 mm downstream of the nozzle exit plane. For a laser power of about 10 kW a fairly good agreement is obtained between experimental dots and the calculated solid line. In order to interrogate the active flow with respect to possible gradients, a 10 mm wide slit has been positioned at 9, 17 mm and 25 mm downstream of the nozzle exit plane, respectively. Results are compared with the fully opened resonator (open circles) and, since no significant deviations are found this leads to the conclusion that the flow conditions are fairly constant within the optical cavity.

2.2 Liquid jet singlet oxygen generator

In recent years considerable effort has been devoted to the investigation and development of so-called jet-type oxygen generators invented by Russian researchers at the Samara Branch of the Lebedev Institute. In order to derive a figure of merit for the jet generator the efficiency of all published devices has been plotted in Fig. 11 as a function of the reaction time of the BHP jets with the chlorine gas. However, 22 different data points do not really exhibit any characteristic behavior. In conclusion, the reaction time is not the expected figure of merit; thus this unanswered question remains to be considered in all the efforts dedicated to the development of jet generators. In Germany, a small scale generator with 49 liquid jets of 0.5 mm ∅ and a typical length between 10 cm and 15 cm has been investigated. A picture of the experimental device is shown in Fig. 12. Utilization, yield, and generator efficiency have been plotted in Fig. 13 as a function of distance from the exit of the generator. At a total pressure of 90 mbar for a helium/oxygen mixture, efficiencies of up to 60% have been demonstrated at the generator exit. Further investigations with special emphasis on scaling properties are under way.

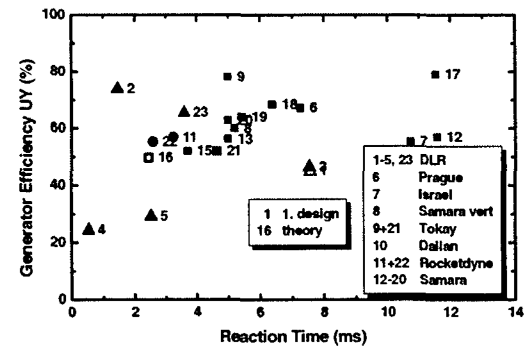

Fig. 11: Survey of jet generator efficiency.

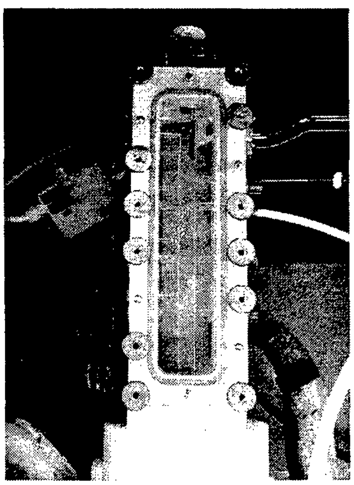
Fig. 12: Jet generator device.

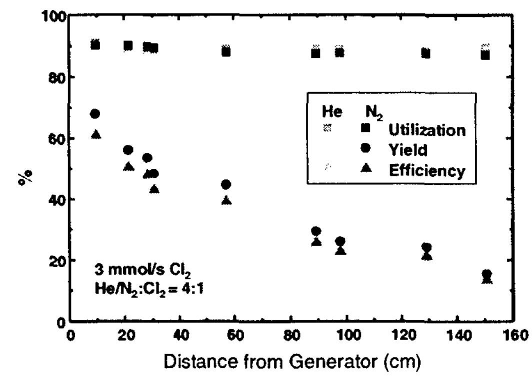

Fig. 13: Performance data of jet generator.

3. PRESENT AND FUTURE APPLICATIONS

3.1 Beam quality issue

Since most of the laser applications require high beam quality a survey is given in Fig. 14 of the beam quality factor, M^2, related to either commercially available lasers (full symbols) or laboratory devices (open symbols). The data collection covers CO_2 gas lasers, lamp and diode pumped solid state lasers, fiber lasers, and a novel thin disk solid state laser. As the output power increases only CO_2 lasers keep a beam quality better than 10 times the diffraction limit. For comparison two COIL beam quality values have been added: one has been reported by the Dalian Group in China and the other one has been advertised (but never officially published) by the AFRL in the U.S. Fig. 14 very clearly shows the lack of brightness property of present solid state lasers and the huge brightness potential suggested by COIL technology. In order to overcome the problem of small signal gain in moderate sized COIL devices we currently

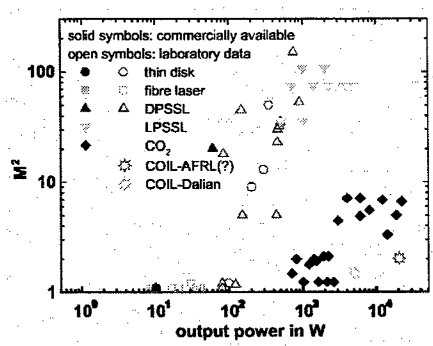

Fig. 14: Beam quality factor survey.

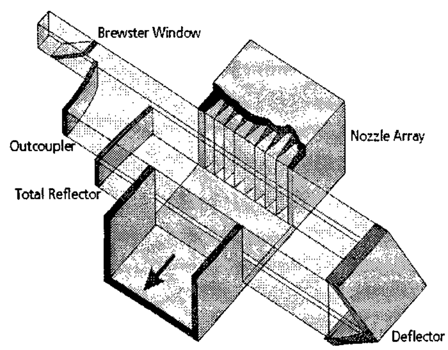

Fig. 15: Layout of folded hybrid resonator.

investigate a folded hybrid resonator scheme as shown in Fig. 15. This resonator is unstable in flow direction and stable in the direction of the nozzle exit plane. A folded beam path should sustain enough gain in order to efficiently operate the laser. First experimental investigations have not yet been successful due to the high alignment sensitivity associated with this particular resonator concept.

3.2 Tactical air defense

Germany has engaged into a national demonstrator program based on the technology reviewed in chapter 2.1. This effort is a container based approach aimed at the evaluation of COIL technology for future air defense applications. The system covers all the necessary infrastructure for proper laser operation, a target acquisition system, and a tracking and pointing system including atmospheric turbulence corrections using adaptive optics. This program is primarily carried out by German industrial companies and supported by the German government.

3.3 Space debris removal

Considering the pulsed operation capability of COIL a study has been undertaken to define the potential of a larger COIL system for spaced debris removal from ground. Enhanced peak power by gain switching a 3 kW CW COIL has been demonstrated by Hager[6] et al. in 1994. The demonstrated enhancement factor was about 13 with respect to the CW value. Assuming a slightly more optimistic enhancement factor of 15 and a mechanical coupling coefficient of $C_m = 3$ for repetitively pulsed laser operation vs. $C_m = 1$ for CW operation we have derived COIL requirements for space debris removal. In Fig. 16 the minimum average power is plotted as a function of the diameter of the beam director. Two different debris removal scenarios have been considered. Firstly, the ORION[7] scenario which is aimed at removing the debris at an altitude of 1000 km. In the ORION concept suggested by Phipps et al. a 20 kW average power beamlet fusion laser is being used; the dotted lines exhibit the power requirement of a repetitively pulsed COIL assuming a mechanical coupling of 3 and 1, respectively. Secondly, the Falcon[8] scenario is intended to remove debris at an altitude of 450 km using a 5 MW CW nuclear pumped laser. In contrast, a repetitively pulsed COIL requires average powers as shown by the two full lines with different mechanical coupling coefficients. In summary, a scaled up COIL technology provides an interesting alternative to the space debris removal issue as compared to the ORION and Falcon concepts, respectively[9].

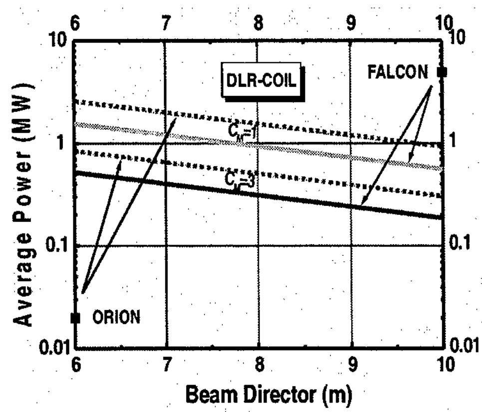

Fig. 16: Required average COIL power for debris removal.

3.4 Decommissioning of nuclear installations

The potential COIL advantages for applications in the area of decommissioning are obvious:

- -scalable in power
- -high beam quality
- -fiber optic beam delivery
- -robotic/remote processing capability
- -efficient material interaction due to short wavelength.

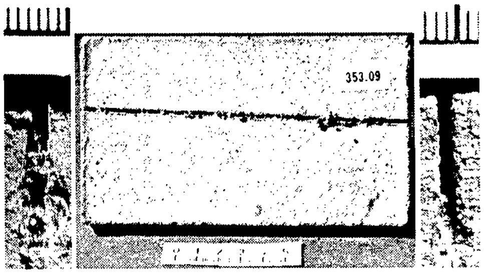

Fig. 17: Cutting concrete at 1.3 μm

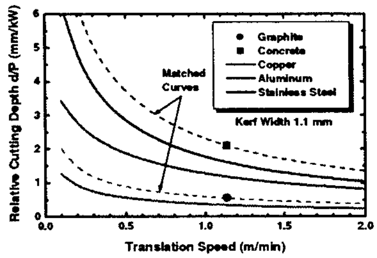

Fig. 18: Modeling of cutting speed for different materials.

Whereas the three last positions are valid for present solid state lasers, the two first positions may only be matched by COIL technology in the near future. First experiments have been undertaken with the 10 kW DLR COIL in order to demonstrate its capability of cutting concrete. A sample is shown in Fig. 17 with a cutting depths of about 5 cm. Using available models we have tried to predict COIL cutting performance in materials relevant to decommissioning applications. Since no data base is available for those materials we have derived our calculations by anchoring the model to our experimental points. As deduced from Fig. 18 a 70 kW COIL would be capable of cutting 30 cm of concrete at a speed of 0.4 m/min. In order to further assess the future industrial potential of COIL in the area of decommissioning a comparison of costs with respect to other industrial laser candidates has been undertaken. A brief summary of the results is highlighted in Fig. 19. Although the CO_2 laser appears to be the most attractive low cost candidate it should be mentioned that its wavelength is not suited for fiber optic beam delivery and, thus, he is not a candidate to be seriously considered for the application discussed here. The lamp pumped Nd:YAG laser is still cheaper than COIL but its scalability to high power levels has yet to be demonstrated.

Laser	Investment Costs 1000 € / kW	Running Costs (incl. Depreciation) € / kWh
CO_2	60	10
Nd:YAG (lamp)	125	20
Nd:YAG (diode)	1000	110
COIL	170	50

Fig. 19: Figures for the marketplace.

4. CONCLUSIONS AND OUTLOOK

Successful operation and understanding of COIL at relevant power levels has been achieved. COIL technology has matured to the point that it basically can support an effort aimed at the development of an air defense demonstrator. Furthermore, COIL technology is being considered for future civilian applications, as well.

However, some fundamental issues are presently still unresolved: the iodine dissociation is satisfactorily described in the existing devices but no universal nor scalable model is presently available. Although high beam quality is generally anticipated it needs to be demonstrated along with efficient laser operation. And finally the question arises if the high brightness leading edge of COIL will prevail over the considerable improvements that may occur in solid state laser research for the years to come.

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